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Ecological accounting for an integrated "pig–biogas–fish" system based on emergetic indicators

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ABSTRACT

With the expansion of urbanization in China, the integrated biogas-utilization system has gained its popularity for both renewable energy production and multi-level utilization of organic waste. To appraise the ecological performance of the integrated biogas system, systematic accounting is undertaken for an integrated "pig–biogas–fish" system in Hubei province, China. Based on Odum's concept of embodied solar energy as a unified measure for environmental resources, human labors and purchased goods, a set of emergetic indicators are employed to quantify the system sustainability. The results reveal that in a 20-year designed lifetime scenario, 94.69% of the total emergy inputs for the "pig–biogas–fish" system are attributed to purchased social resources. Three kinds of products, namely pig, biogas, fish are taken into consideration, and transformity of the "pig–biogas–fish" system is calculated as 1.26E + 05 seJ/J. Compared with the Chinese conventional agriculture system, the integrated biogas system shows a higher sustainability. Given that most biogas systems have a lifespan less than 20 years, for the "pig–biogas–fish" system, six other scenarios with different lifespans are studied to investigate the impact of the lifespan on sustainability. The findings suggest that the "pig–biogas–fish" system should be well operated for at least 8 years to prove its advantage in ecological economy over the conventional agriculture system. This has essential policy implications that local government should strengthen subsequent management on biogas production to extend the practical service life of the biogas system.

1. Introduction

Since fossil fuels are limited and consumption of these fuels casts a negative impact on the environment, renewable energy is playing a crucial role in sustainable energy development (Chen and Chen, 2011b). In 2012 alone, global investment in renewables has reached 244 million dollars, 8% above the 2010 level (REN21, 2013). As the world's fourth largest source of energy (following oil, coal, and natural gas), biomass is expected to become the most promising renewable energy source (IEA, 2011). Biogas production, a primary way of using biomass to provide modern energy services, has continued to increase, especially in developing countries (Olugasa et al., 2014).

China has an enduring history of biogas utilization with the first test of biogas fermentation that was undertaken in the 1880s (Yang and Chen, 2014b). Afterwards to address challenges from energy shortage in rural areas, China has been on a constant endeavor to promote the biogas construction. In 2007, the government published the *Medium and Long-Term Development Plan for Renewable Energy*, predicting that some 80 million household biogas digesters would have been installed with a total output of 30 billon m^3 by the end of 2020 (NDRC, 2007). In recent years, with the expansion of rural urbanization in China, waste disposal is becoming a troublesome roadblock in the way (Chen et al., 2012a; Ruan et al., 2006;

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Wu et al., 2012; Yuan et al., 2008). A promising biogas technology is expected to offer energy supply, as well as to achieve multi-level utilization of organic waste (Agostinho and Ortega, 2012; Li et al., 2012; Song et al., 2014; Yang and Chen, 2014a). In this context, the integrated biogas-utilization system, which incorporates biogas fermentation technology into crop production and animal husbandry, has arrested extensive attention.

In the integrated biogas-utilization system, the substrate for anaerobic digestion is from agricultural and household wastes, thus drastically preventing environmental pollution that stems from the wastes discharged directly. After fermentation, biogas finds its application as a clean fuel in households, and biogas residue is recycled to agriculture as an organic fertilizer. The integrated biogas-utilization system has thus realized the maximization of recycling and declared its sound environmental and economic advantages. However, though the integrated system yields energy and goods, it demands materials and work force, particularly free resources from nature as its subsystems of crop production and animal husbandry are heavily dependent on environmental conditions. Therefore, systematic accounting on the integrated system is imperative to be undertaken in order to guarantee a sustainable future. Extensive studies on the ecological accounting of typical biogas systems have been carried out with methods of life cycle assessment (LCA) (Berglund and Börjesson, 2006; Chen and Chen, 2013a,b; Chen et al., 2012b; Poeschl et al., 2012; Rehl et al., 2012) and exergy (Chen and Chen, 2007a; Chen et al., 2009b; Xydis et al., 2013; Yang and Chen, 2014b). These studies have contributed significantly to the development of accounting for renewable energy projects. However, these methods are rarely implemented in full consideration of the resource use due to human labor and environmental work. In contrast, the emergy method that was first proposed by Odum on the basis of a combined system of humanity and nature, could offer an insightful perspective into production system evaluation from a systematic point of view (Brown and Ulgiati, 2004).

Emergy is defined as the available energy of one kind of previously used up in transformations directly and indirectly to make a product or service (Odum, 1983, 1988, 1996). It tracks the total amount of resources required to produce something by tracing all energy flows back to the conventionally accepted Earth's ultimate energy source: solar radiation (Odum, 1994), thus integrating the value of environmental investments, goods, services and information on a common foundation of solar emjoule (abbreviated seJ) and devising scientific indicators to measure its ecological performance. Till now, the emergy method has been performed on the region scale (Higgins, 2003; Lei et al., 2008), the nation scale (Ulgiati et al., 2011; Yang et al., 2010), and the world scale (Brown and Ulgiati, 1999). In addition, some renewable energy technologies have also been evaluated with emergy, such as the hydropower plant (Zhang et al., 2014), the wind power plant (Yang et al., 2013) and the solar power system (Zhang et al., 2012). A few studies have been conducted so far to assess typical biogas systems via the emergy approach. Wei et al. (2009) compared the efficiency and sustainability between a "four in one" peach production system in Beijing and a conventional solar greenhouse peach production system by emergy-based ecological analysis. Ciotola et al. (2011) evaluated a small scale biogas production and electricity generation system in Costa Rica on aspects of sustainability and environmental impacts with emergy indices. Chen and Chen (2012) undertook an emergy evaluation of the efficiency and emission mitigation effect of a biogas-linked agricultural ecosystem in Gongcheng County, China. Then Chen and Chen (2014) proposed a 3-level emergetic evaluation framework to investigate the sustainability of the integrated biogas-utilization system. Wang et al. (2014) introduced life cycle assessment (LCA) into emergy evaluation to analyze each production step of a large-scale biogas project in Hebei province, China. These studies serve as a reflection for the developments of both the emergy analysis and ecological biogas system.

Hubei province is located along the Yangtze River with developed aquaculture industry, and the "pig–biogas–fish" system, a common integrated biogas mode in Hubei is chosen as a case in this paper. As an extension for our work on fossil energy cost of purchased goods in the "pig–biogas–fish" system (Yang et al., 2012), this study presents systematic accounting and indicators of the "pig–biogas–fish" system via the emergy method to estimate environmental and economic inputs and to assess the sustainability of this system. Nowadays, the latest systematic multi-scale embodied ecological elements databases including different kinds of productions in China have been published by Chen and his research group (Chen and Chen, 2007b, 2009b, 2010, 2011a; Chen et al., 2011a, 2011b, 2011c, 2011d, 2013; Han et al., 2013; Li and Chen, 2013; Li et al., 2013, 2014; Meng et al., 2014; Shao and Chen, 2013; Shao et al., 2013; Yang et al., 2009; Yang and Chen, 2012, 2013; Zhou, 2008), and are thus applied in this research to improve the accuracy and avoid repeatability of emergy accounting. Besides, the operational time of the biogas digester is assumed as 21 years (Zhou et al., 2010) or 20 years (Wu et al., 2013) in previous papers, but actually, it does not always tally with the fact. In this case, this paper tries to take account of the impact of the lifespan on sustainability for a more accurate analysis.

The rest of this paper is organized as follows. After an introduction of the case study and the emergy method in Section 2, we present the system performance of the case based on emergy evaluation indicators and discuss major findings in Section 3. Finally, in Section 4 some concluding points of this study are presented.

2. Materials and methods

2.1. The case biogas system description

The household biogas system under consideration is the biogas energy and animal husbandry linked agro-ecosystem in Zhongzhouzi fishery, Jinzhou City (111°15′–114°05′E, 29°26′–31°37′N), Hubei province, which we call a "pig–biogas–fish" system. Jinzhou is an important port city and freshwater fishery base along the Yangtze River, and is known as "the land of plenty" in China, with an annual average sunlight time of 1978 h. The annual average temperature is 17.8 °C, with the lowest winter temperature going down to −3.0 °C and the highest temperature climbing up to 38.4 °C in summer. The annual average precipitation is 1300 mm (Jingzhou, 2002). In recent years, Jinzhou is committed to developing ecological agriculture, and chooses Zhongzhouzi fishery as an exemplary demonstration area for the household "pig–biogas–fish" system. Up to 2010, the demonstration area has been extended to 0.6 million m^2 and the income of residents has increased by 6.2 million RMB in total compared to the year 2008.

As shown in Fig. 1, the "pig–biogas–fish" system consists of a pigsty, a biogas pool and a fishpond. The workflow is as follows: through raising pigs, residents put the pig manure into the digester as the fermentation crude to produce biogas for everyday lighting and cooking. Meanwhile, the biogas slurry and residue can be used as a base fertilizer and top dressing for the fishpond. The details have been introduced in our previous work (Yang et al., 2012). This system is designed with an operational life of 20 years. Given the poor management, however, it is not capable of working for 20 years (Liu and Feng, 2013). In China, the government has offered local residents sufficient technological guidance and subsidy for biogas promotion at the beginning of the construction, but subsequent management guidance is often neglected.

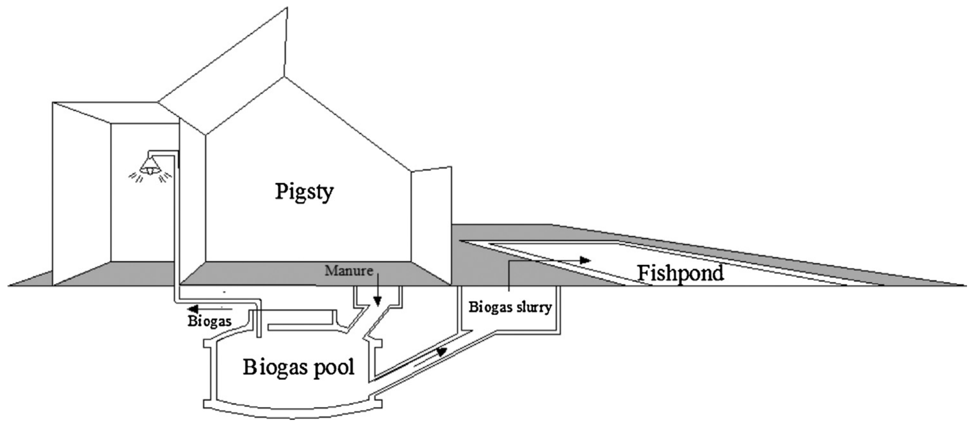

Fig. 1. Schematic diagram of the "pig–biogas–fish" system.

2.2. Emergy analysis

Odum's emergy synthesis is a thermodynamic approach for the ecological evaluation of resources, products and services by accounting the total natural work (Chen and Chen, 2006; Chen et al., 2010; Sciubba and Ulgiati, 2005). On the one hand, the emergy method focus on the role of the environment in support of human-dominated processes, which can be used as a supplement to the money-based economic evaluation that takes only the contribution from social economy into consideration. On the other hand, totally different from conventional energy analysis which merely accounts for the remaining available energy at present, the emergy method expands the time scale of the evaluation to include the memory of resource flows converging to the system. Detailed process of emergy accounting has been given by some researchers (Chen et al., 2006; Zhou et al., 2009). For the "pig–biogas–fish" system, the first step is to draw an overview emergy diagram to define the boundary of the given system and identify the inputs and outputs to be evaluated on basic symbols presented by Odum. As described in Fig. 2, the total emergy inputs are generally aggregated into four categories: free environmental renewable resources (*RR*), free environmental nonrenewable resources (*NR*), purchased social renewable inputs (*RP*) and purchased social nonrenewable inputs (*NP*). The total emergy use (*U*) is equal to the sum of emergy inflows (*RR* + *NR* + *RP* + *NP*). Correspondingly, produced energy (*Ep*) denotes the output of total energy produced by the "pig–biogas–fish" system. Besides, pig manure and biogas residues are recycled in this system, and these two intermediate materials are regarded as the internal force that drives emergy to transfer from pigsty to biogas pool and then from biogas pool to fishpond, hence system feedback emergy (*SF*) represents the communication emergy within this system.

The second step for emergy analysis is to obtain the emergy value of each item considered in the "pig–biogas–fish" system. In this step, all inputs with raw data such as joules, kilograms or dollars are converted into solar emergy with the unit of seJ. And for this conversion, Unit Emergy Value (*UEV*), also regarded as emergy intensity, is defined as the solar emergy required to make per unit (joule or mass or money) of a product or service (Brown and Ulgiati, 2004), thus total emergy use (*U*) in the biogas system can be calculated as

$$U = \sum u_i = \sum p_i \times UEV_i \tag{1}$$

where u_i denotes the emergy associated directly and indirectly with the production of the *i*th product, p_i, to the entire process of the system. It should be noted that *UEV*s for a wide variety of goods and services can be obtained from previous studies to facilitate the emergy analysis. However, *UEV* of a given object may have different values due to the specific geographic location and production process. As the first endeavor in embodied ecological elements accounting of Chinese national economy, Zhou (2008) offered a systematic *UEV* database consisting of 151 physical goods by combining the input-output analysis with ecological thermodynamics (see Appendix). To avoid dispersed and inappropriate *UEV*s and to guarantee the accuracy of emergy analysis in this study, *UEV*s of materials and resources associated with the investigated biogas system are mainly from Zhou's database.

The final step is to establish an emergetic indicator framework and to quantify ecological behaviors of the "pig–biogas–fish" system, which will be elucidated in detail below.

The global emergy sustaining the biosphere is also regarded as the emergy base of reference, which was previously calculated as 9.44E + 24 seJ/yr (Odum, 1996), and then updated as 1.58E + 25 seJ/yr (Odum et al., 2000) and 1.52E + 25 seJ/yr (Brown and Ulgiati, 2010). In the following we adopt the Brown and Ulgiati (2010) baseline, and *UEV*s prior to the year 2010 are multiplied by 1.61 (the ratio of 1.52E + 25/9.44E + 24) or 0.96 (the ratio of 1.52E + 25/1.58E + 25) for conversion to the new baseline.

2.3. Emergetic indicators

On the basis of the fluxes mentioned above (*RR*, *NR*, *RP*, *NP*, *U*, *Ep*, *SF*), a series of indicators are introduced as follows to present the system performance of the "pig–biogas–fish" system (Chen et al., 2009a; Jiang et al., 2008; Ulgiati et al., 1995)

$$\text{transformity}\,(Tr) = \frac{U}{Ep} \tag{2}$$

Transformity (*Tr*), a type of *UEV*, is defined as the emergy input per unit of available energy output (Odum and Odum, 2000) with a unit of seJ/J. It is obtained by the ratio of total emergy used in a process to the energy yielded by the process. *Tr* is an expression of the quality of the output itself. The higher the transformity, the more emergy is required to make the product flow.

$$\text{renewable percentage index}\,(Pr) = \frac{RR + RP}{U} \tag{3}$$

Different from the percent renewable index as the ratio of *RR* to *U* presented by Brown and Ulgiati (1997), a modified renewable percentage index (*Pr*) is defined as the ratio of all renewable emergy inputs free or purchased to the total emergy inputs and it illustrates renewable contribution in the total inputs of the given

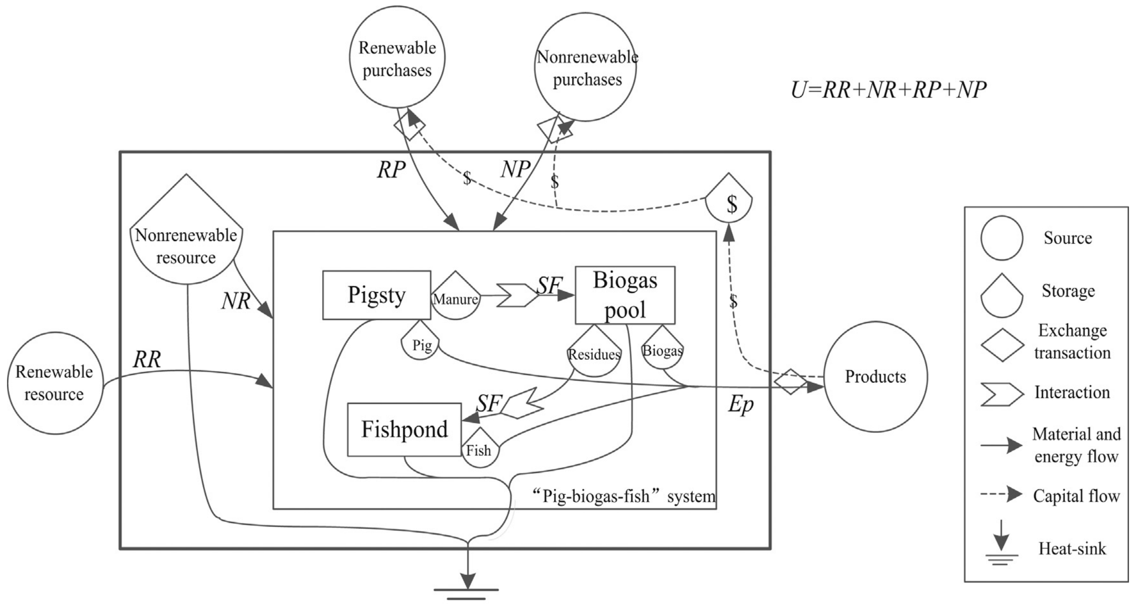

Fig. 2. Aggregated emergy flow diagram for the "pig–biogas–fish" system.

system (Chen and Chen, 2009a). A system with higher *Pr* is considered more sustainable in the long run.

$$\text{emergy yield ratio}\,(EYR) = \frac{U}{RP + NP} \tag{4}$$

EYR is the ratio of total emergy cost to the purchased emergy from the outside economy, which represents the efficiency of a process using purchased inputs to exploit natural resources. The higher the index, the greater the return is obtained per unit of emergy invested.

$$\text{environmental load ratio}\,(ELR) = \frac{NR + NP}{RR + RP} \tag{5}$$

ELR is the ratio of the total emergy of nonrenewable inputs to the total emergy of renewable inputs, which indicates the stress of the given system on the environment. And the lower the ratio, the lower the stress is on the environment.

$$\text{environmental sustainability index}\,(ESI) = \frac{EYR}{ELR} \tag{6}$$

ESI takes both ecological and economic compatibility into account, and it indicates whether a process provides due contribution to the user with a low environmental pressure, reflecting the overall sustainability of a production process. The higher the index, the higher the sustainability of the system is.

$$\text{emergy feedback ratio}\,(EFR) = \frac{SF}{RP + NP} \tag{7}$$

It is the ratio of system feedback yield emergy to the purchased emergy from the economy, which represents the self-organization ability of the system. The higher the index, the stronger the inner drive is in the system (Wei et al., 2009).

3. Results and discussion

3.1. Emergy accounting

Corresponding to Fig. 2, Table 1 lists the evaluated emergy values of the aggregated flows associated with the "pig–biogas–fish" system, and takes one year as the time cycle for a 20-year designed operation scenario. Five free renewable resources inflowing to the "pig–biogas–fish" system are calculated in free renewable resources (*RR*) accounting, but to avoid double accounting, only the item with the highest value is adopted (Odum, 1996). And in this research, the earth cycle energy is the largest one compared with solar radiation energy, kinetic energy of wind, chemical energy of rain and gravitational potential energy of rain, so its value (6.48E + 14 seJ/yr) is taken as *RR* inputs. For free nonrenewable resources (*NR*) accounting, 1.12E + 14 seJ/yr, the main concern is nutrition from the natural topsoil losses and the soil degradation, which serves as the fundamental support for this ecological agriculture system.

Purchased social inputs (*RP* + *NP*) include those bought from the economy, such as electricity, fertilizer and human labor. And renewable percent of each item is listed in Column 1, Table 1 according to Chen and Chen (2010), which provides a detailed calculation of the renewable and nonrenewable emergy inputs of 135 sectors in China with an ecological input–output modeling. Swine manure in the pigsty system and biogas residues in the biogas pool system are counted as system feedback (*SF*), and they amount to 1.31E + 15 seJ/yr, implying that 1.31E + 15 seJ of emergy is recycled in internal system every year and helps propel its self-organization. Produced energy (*Ep*), 1.13E + 11 J/yr, mainly comprises three products, namely pig, biogas and fish, among which pig and fish are imported into the market directly, and biogas is used by the household and helps cut down the amount of coal bought from the market.

The results show that the total emergy inputs (*U*) of the "pig–biogas–fish" system are 1.43E + 16 seJ/yr (1.38E + 16 seJ/yr without L&S), and among them the major emergy inputs are ascribed to purchases (*RP* + *NP*), 1.35E + 16 seJ/yr with the largest percentage of 94.69%. As shown in Fig. 3, *RR* accounts for 4.53% of the total emergy inputs, while *NR* takes up 0.78%. Both *RR* and *NR* are supplied by the free environment and denote the direct support from the nature. The two parts are calculated as 7.60E + 14 seJ/yr altogether. Besides, the purchases can be divided into four parts: labor and services; the pigsty system; the biogas pool system and the fishpond system. Emergy inputs of the fishpond system are 9.17E + 15 seJ/yr, taking the largest share (64.16%) of the total emergy, and they are mainly caused by materials used in operation and maintenance phases because emergy associated with fish feed and fertilizer takes up 70.24% of total emergy in fishpond system.

Table 1
Emergy accounting for the "pig–biogas–fish" system.

Class	Item	*p*	Unit	*UEV* (seJ/unit)	*u* (seJ/yr)
Renewable resources from free environment (*RR*)					
100.00%R	Solar radiation	2.51E + 13[a]	J/yr	1.00E + 00	2.51E + 13
100.00%R	Wind (kinetic)	2.85E + 09[b]	J/yr	2.41E + 03[c]	6.87E + 12
100.00%R	Rain (chemical)	1.01E + 10[d]	J/yr	2.93E + 04[c]	2.96E + 14
100.00%R	Rain (geopotential)	3.66E + 08[e]	J/yr	1.69E + 04[c]	6.18E + 12
100.00%R	Earth cycle	1.17E + 10[f]	J/yr	5.54E + 04[c]	6.48E + 14
Subtotal					6.48E + 14
Nonrenewable resources from free environment (*NR*)					
0.00%R	Soil loss	9.39E + 08[g]	J/yr	1.19E + 05[c]	1.12E + 14
Subtotal					1.12E + 14
Purchased social renewable and nonrenewable inputs (*RP* + *NP*)					
34.65%R[h]	Labor and services (L&S)	5.08E + 01[i]	$/yr	9.45E + 12[j]	4.80E + 14
Pigsty					
9.06%R[h]	Cement and bricks	1.90E + 01	kg/yr	4.88E + 11[k]	9.27E + 12
9.06%R[h]	Lime	1.25E + 01	kg/yr	5.41E + 12[k]	6.76E + 13
4.35%R[h]	Steel	2.63E + 00	kg/yr	5.20E + 12[k]	1.37E + 13
85.10%R[h]	Feed	1.20E + 03	kg/yr	2.16E + 12[k]	2.59E + 15
29.33% R[h]	Drugs	4.80E − 02	kg/yr	1.58E + 14[k]	7.58E + 12
29.33%R[h]	Disinfectant	4.00E − 01	kg/yr	1.02E + 13[k]	4.08E + 12
75.70%R[h]	Water	5.66E + 04	kg/yr	7.49E + 08[k]	4.24E + 13
21.29%R[h]	Electricity	2.30E + 08	J/yr	5.06E + 05[k]	1.16E + 14
Biogas pool					
9.06%R[h]	Cement	4.50E + 01	kg/yr	4.88E + 11[k]	2.20E + 13
33.27%R[h]	Sand and pebble	5.00E + 01	kg/yr	1.61E + 09[c]	8.05E + 10
12.46%R[h]	Plastic pipe	4.00E + 00	kg/yr	9.85E + 12[k]	3.94E + 13
4.35%R[h]	Steel mold	1.25E + 02	kg/yr	7.76E + 12[k]	9.70E + 14
Fishpond					
9.06%R[h]	Lime	1.80E + 02	kg/yr	5.41E + 12[k]	9.74E + 14
11.93%R[h]	Bleach	3.20E + 00	kg/yr	1.02E + 12[k]	3.26E + 13
23.80%R[h]	Aerator	5.00E − 02	set/yr	3.45E + 16[k]	1.72E + 15
85.10%R[h]	Feed	1.95E + 03	kg/yr	2.16E + 12[k]	4.21E + 15
13.80%R[h]	Nitrogen fertilizer	2.00E + 02	kg/yr	5.23E + 12[k]	1.05E + 15
13.80%R[h]	Phosphate fertilizer	1.00E + 02	kg/yr	1.19E + 13[k]	1.19E + 15
Subtotal					1.35E + 16
System feedback (*SF*)					
	Swine manure	8.42E + 09[l]	J/yr	2.60E + 04[m]	2.19E + 14
	Biogas residues (N)	5.52E + 01[n]	kg/yr	5.23E + 12[k]	2.89E + 14
	Biogas residues (P)	6.72E + 01[n]	kg/yr	1.19E + 12[k]	7.97E + 14
Subtotal					1.31E + 15
Produced energy (*Ep*)					
	Pig	9.80E + 09[o]	J/yr		
	Biogas	1.00E + 10[p]	J/yr		
	Fish	9.34E + 10[q]	J/yr		
Subtotal		1.13E + 11	J/yr		
U (with L&S)		1.43E + 16	seJ/yr		
U (without L&S)		1.38E + 16	seJ/yr		

[a] Solar energy = (area) × (average insolation) × (1 − albedo) = (5.32E + 03 m^2) × (5.90E + 09 J/m^2/yr) × (1–20%) = 2.51E + 13 J/yr.
[b] Wind energy = (area) × (density of air) × (average annual wind velocity)^3 × (annual working time) × (drag coefficient) = (5.32E + 03 m^2) × (1.23 kg/m^3) × (2.40 m/s)^3 × (3.15E + 07 s/yr) × (0.001) = 2.85E + 09 J/yr.
[c] Refer to Odum (1996) with the baseline of 9.26E + 24 seJ/yr. *UEV*s adopted from that paper is multiplied by 1.61 for conversion to the new baseline.
[d] Rain energy (chemical) = (area) × (evapotranspiration) × (rain density) × (Gibbs free energy) = (5.32E + 03 m^2) × (3.86E − 01 m/yr) × (1.00E + 03 kg/m^3) × (4.94E + 03 J/kg) = 1.01E + 10 J/yr.
[e] Rain energy (geopotential) = (area) × (rainfall) × (runoff rate) × (average elevation) × (rain density) × (gravity) = (5.32E + 03 m^2) × (1.30 m) × (20%) × (2.70E + 01 m) × (1.00E + 03 kg/m^3) × (9.80 m/s^2) = 3.66E + 08 J/yr.
[f] Energy of earth cycle = (area) × (heat flow) × (annual working time) = (5.32E + 03 m^2) × (7.00E − 02 W/m^2) × (3.15E + 07 s/yr) = 1.17E + 10 J/yr.
[g] Lost energy = (area) × (total soil loss per year in China)/(National territory area) × (average organic content) × (energy content/g organic) = (5.32E + 03 m^2) × (5.00E + 15 g/yr)/(9.60E + 10 m^2) × (1.5%) × (2.26E+01 J/g) = 9.39E + 08 J/yr.
[h] Refer to Chen and Chen (2010).
[i] Labor and services = (area) × (average wage) × (exchange rate between RMB and $ in 2004) = (5.32E + 03 m^2) × (7.90E − 02 RMB/m^2/yr) × (1.21E − 01 $/RMB) = 5.08E + 01 $/yr.
[j] Refer to Yang et al. (2010) with the baseline of 9.26E + 24 seJ/yr. *UEV*s adopted from that paper is multiplied by 1.61 for conversion to the new baseline.
[k] Refer to Zhou (2008) with the baseline of 9.26E + 24 seJ/yr. *UEV*s adopted from that paper is multiplied by 1.61 for conversion to the new baseline.
[l] Energy of swine manure = (manure per year) × (organic matter content) × (standard energy value) = (4.16E + 03 kg/yr) × (15%) × (1.35E + 07 J/kg) = 8.42E + 09 J/yr.
[m] Refer to Wei et al. (2009) with the baseline of 1.58E + 25 seJ/yr. *UEV*s adopted from that paper is multiplied by 0.96 for conversion to the new baseline.
[n] Refer to Lin et al. (2008).
[o] Energy of pig = (output) × (calorific value) = (1.00E + 03 kg/yr) × (2.34E + 03 Kcal/kg) × (4.19E + 03 J/Kcal) = 9.80E + 09 J/yr.
[p] Energy of biogas = (output) × (calorific value) = (4.00E + 02 m^3/yr) × (2.50E + 07 J/m^3) = 1.00E + 10 J/yr.
[q] Energy of fish = (output) × (calorific value) = (9.60E + 03 kg/yr) × (2.33E + 03 Kcal/kg) × (4.19E + 03 J/Kcal) = 9.34E + 10 J/yr.

The second largest contribution (19.94%) to the total emergy is from the pigsty system for materials used in construction, operation and maintenance phases. But for the biogas pool system, only materials used to construct the biogas digester are counted here since raw materials for fermentation can be supplied by the pigsty system, and the biogas pool system takes up 7.22%. Labor and services part, the part referring to construction manpower and labor for operation, accounts for a proportion of 3.36%. In this part, human labor and society service are linked up to nature, and this part is an important part in the environmental accounting, although usually neglected in traditional energy analysis.

Table 2
Comparison of *Tr* of some typical biogas systems.

No.		Location	Lifetime (yr)	*Tr* (seJ/J)
1	Wei et al. (2009)[a]	Beijing, China	20	1.98E + 05
2	Ciotola et al. (2011)[b]	Earte University, Costa Rica	20	8.73E + 04
3	Chen and Chen (2012)[a]	Guangxi, China	20	3.63E + 05
4	Wu et al. (2013)[b]	Shanxi, China	20	2.40E + 06
5	This study	Hubei, China	20	1.26E + 05

[a] Relative to the baseline of 1.58E + 25 seJ/yr. *Tr* in that paper is multiplied by 0.96 for conversion to the new baseline.
[b] to the baseline of 9.26E + 24 seJ/yr. *Tr* in that paper is multiplied by 1.61 for conversion to the new baseline.

3.2. Transformaty (Tr)

Tr is a crucial parameter, which denotes the overall efficiency of the system. Those with greater transformities demand more emergy to generate the same amount of products. For the “pig–biogas–fish” system, *Tr* is calculated as 1.26E + 05 seJ/J. Table 2 lists *Tr*s of some typical biogas systems in previous studies. Given that the baseline adopted has a direct impact on the value of *Tr*, all *Tr*s in Table 2 are converted to the common baseline of 1.52E + 25 seJ/yr to make them comparable. Some numerical variations can be seen in the table, and they are mainly attributed to the differences in production efficiency and the different values of *UEV*s adopted in emergy analysis.

Apart from the reasons mentioned above, some other factors are also responsible for the differences. The “four in one” biogas system in the first study in Table 2 included a solar greenhouse for the cold weather during winter time in northern China, which increased emergy inputs of this biogas system. This also reflects that the warm-wet climate in southern China can help improve the efficiency of biogas systems. The second research took the biogas digester as the research object rather than the integrated biogas-utilization system, and only the emergy investment associated with the digester was considered, so *Tr* in that paper is smaller than that in our study. And it proves that the biogas energy utilization has a higher efficiency considering the lower *Tr*. The biogas-linked agricultural ecosystem introduced by the third paper added the five free renewable emergy inputs, i.e. solar radiation, rain (chemical), rain (geopotential), wind (kinetic) and earth cycle together in *RR* accounting, which is different from the calculation in this paper. Also, the fourth study used the sum of the five free renewable emergy inputs as *RR* inflow. Besides, the biogas was calculated as a kind of feedback rather than a product in that study. However, the differences between these researches can offer insight into the performance of the biogas technology from different perspectives.

3.3. Emergy-based indicators

Listed in Table 3 are emergy fluxes and indicators of the “pig–biogas–fish” system. *Pr* of the “pig–biogas–fish” system is 52.66%, while it is 25.00% for the conventional agriculture system in China (Jiang et al., 2007), implying that for the total inputs, the ratio of renewable inputs in the “pig–biogas–fish” system is larger than that in the conventional agriculture system and that the integrated biogas-utilization system can reduce consumption of nonrenewable energy by making full use of renewable energy. *EYR* of the “pig–biogas–fish” system is 1.06, which implies that 0.06 unit of free environmental resources can be exploited when one unit of purchased inputs is invested in this system. *ELR* of the “pig–biogas–fish” system is 0.90, indicating that nonrenewable emergy used in this biogas system is less than the renewable one.

Moreover, combining *EYR* with *ELR*, *ESI* gives a comprehensive analysis on the sustainability of this system, and it is calculated as 1.17, higher than that of the conventional agriculture system (0.74) (Jiang et al., 2007), demonstrating that the integrated biogas-utilization system has a higher sustainability. Last but not least, index *EFR* illustrates that the system feedback emergy of the “pig–biogas–fish” system is 9.64% of the purchased emergy, and it also manifests that recycled materials can decrease the purchased inputs by 9.64%.

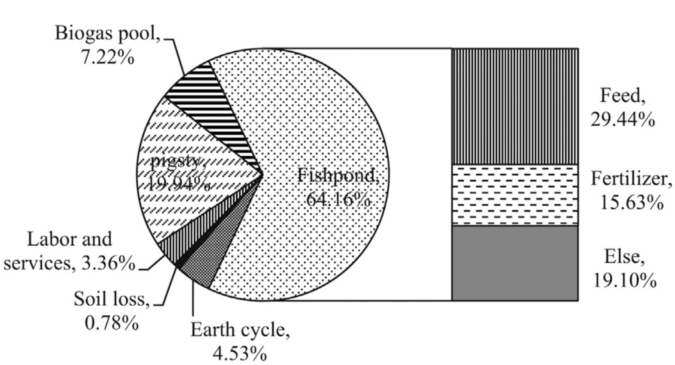

Fig. 3. Fractions of emergy inputs for the “pig–biogas–fish” system.

3.4. Impacts of operation time

The advantages of the “pig–biogas–fish” system are discussed above in the optimal scenario of 20-year stable operation. However, most of the biogas projects suffer from a high rate of obsolescence after 3 years of operation (Liu and Feng, 2013; Zhang et al., 2013). And to determine the influence of lifespan on sustainability for this integrated biogas-utilization system, six other scenarios with different running times from 5 years to 10 years are shown in Fig. 4 below.

The sustainability of the six scenarios is presented with *ESI* index, which is calculated following the emergy accounting process introduced in Section 2. Since one year is chosen as the time span, for each scenario, the construction materials and machinery used in the whole biogas system are converted to annual flows according to its service life that ranges from 5 to 10 years. As pointed out in Eq. (6), the higher the index of *ESI*, the higher the sustainability of the system is. It can be witnessed that sustainability of

Table 3
Emergy fluxes and indicators for the “pig–biogas–fish” system.

Flux	Value	Unit
Free renewable emergy (*RR*)	6.48E + 14	seJ/yr
Free nonrenewable emergy (*NR*)	1.12E + 14	seJ/yr
Purchased renewable emergy (*RP*)	6.88E + 15	seJ/yr
Purchased nonrenewable emergy (*NP*)	6.65E + 15	seJ/yr
Total emergy use (*U*)	1.43E + 16	seJ/yr
Total feedback (*F*)	1.31E + 15	seJ/yr
Indicator	**Value**	
Renewable percentage index (*Pr*)	52.66%	
Emergy yield ratio (*EYR*)	1.06	
Environmental loading ratio (*ELR*)	0.90	
Environmental sustainability index (*ESI*)	1.17	
Emergy feedback ratio (*EFR*)	9.64%	

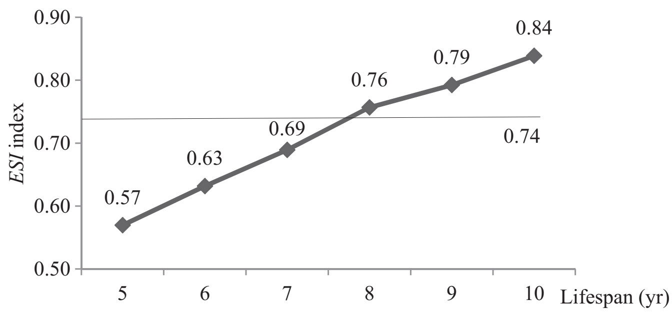

Fig. 4. Sustainability of the six scenarios with different running times.

the biogas system is closely correlated with its lifespan that the longer the working time is, the higher the sustainability is. *ESI* of the "pig–biogas–fish" system with 5 years of operation life is 0.57, while it is 0.84 for the system with 10 years of working life, increasing by 47.37%.

There are two main reasons behind this dynamic trend. The first one is the higher index of *EYR* for the scenario with longer operation life (Fig. 5). Regarding the construction materials invested in the construction process and the machinery bought at the beginning of the operation process, the total amount of them is constant in all scenarios, but the annual amounts of them are different in six scenarios due to the different lifespans. As the lifespan of the biogas system enlarges, the annual flows associated with the construction materials and the machinery decrease in inverse proportion, leading to the same amount of reduction of both purchased emergy ($RP+NP$) and the total emergy inputs (U) and consequently the increase of *EYR*. The other one is the decline in *ELR*, also depicted in Fig. 5. It is attributed to the small renewable percent of the construction materials and the machinery. When annual flows decrease in the above case, the nonrenewable part of purchased emergy (*NP*) declines faster than the renewable part (*RP*). In summary, the longer the operation time of the biogas system is, the greater the return is obtained per unit of emergy investment and the lower the pressure is caused on the environment. Since *ESI* is the ratio of *EYR* to *ELR*, the numerator increases while the denominator decreases, resulting in a rise in sustainability.

The line of 0.74 standing for *ESI* of the conventional agriculture system (Jiang et al., 2007) is presented in Fig. 4 to make a comparison. The "pig–biogas–fish" systems in two adjacent scenarios, i.e. the 7-year lifespan and the 8-year lifespan demonstrate a gain or loss on the contrary. The 7-year scenario has a lower sustainability than the conventional agriculture system, implying an adverse effect on the sustainable development of the agriculture, while the 8-year scenario has a favorable impact. It is therefore projected that the "pig–biogas–fish" system should work normally for at least 8 years to prove its benefit in sustainability.

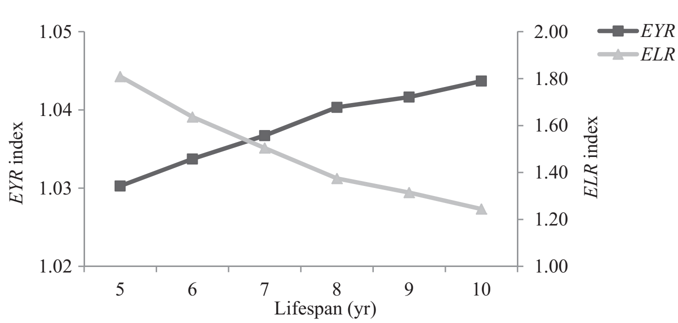

Fig. 5. *EYR* and *ELR* for the six scenarios with different running times.

In fact, only a small proportion of biogas systems can work for 8 years or more than 8 years to exhibit their advantages in sustainability. The high rate of obsolescence is mainly due to a lack of follow-up service and management of biogas digesters. In China, the development of household biogas projects mostly focuses on the construction and fails to take management into consideration, and local governments care more about the development than utilization for the social benefit. Another severe fact is that most residents in China have little knowledge and training in household biogas production. Therefore, an endeavor to provide follow-up service is urgent to ensure the favorable function of digesters and the maximum sustainable benefits of biogas systems. In addition, the governments should also direct full attention to the management and try to change the work center.

4. Concluding remarks

This paper undertakes a systematic accounting and provides ecological indicators for an integrated "pig–biogas–fish" system by employing the emergy method. Emergy provides a more complete coverage of the dimensions of sustainability by considering different forms of materials, environmental support, human labor and economic services on a common basis. For this biogas system, the aggregated emergy flow diagram, systematic accounting tabulation and ecological indicator framework are exhibited separately. The results show that for the "pig–biogas–fish" system with a lifespan of 20 years, *Tr* is calculated as 1.26E + 05 seJ/J and the sustainability indicator, *ESI* is 1.17. When compared with the conventional agriculture system in China, the "pig–biogas–fish" system displays its superiority for the favorable ecological advantages.

Since most of the household biogas systems cannot work for 20 years before they are obsoleted, the impact of lifespan on sustainability for the "pig–biogas–fish" system is discussed in this paper. It reveals that the "pig–biogas–fish" system should be well operated for 8 years to obtain a higher sustainability than the conventional agriculture system. Therefore, the local government needs to improve follow-up service and management of biogas fermentation technology to ensure a longer service life of the biogas system.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.04.033.

References

Agostinho, F., Ortega, E., 2012. Integrated food, energy and environmental services production as an alternative for small rural properties in Brazil. Energy 37, 103–114.

Berglund, M., Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenergy 30, 254–266.

Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69.

Brown, M.T., Ulgiati, S., 1999. Emergy evaluation of the biosphere and natural capital. Ambio 28, 486–493.

Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecol. Modell. 178, 201–213.

Brown, M.T., Ulgiati, S., 2010. Updated evaluation of exergy and emergy driving the geobiosphere: a review and refinement of the emergy baseline. Ecol. Modell. 221, 2501–2508.

Chen, B., Chen, G.Q., 2006. Ecological footprint accounting based on emergy—a case study of the Chinese society. Ecol. Modell. 198, 101–114.

Chen, B., Chen, G.Q., 2007a. Resource analysis of the Chinese society 1980–2002 based on exergy—Part 2: Renewable energy sources and forest. Energy Policy 35, 2051–2064.

Chen, B., Chen, G.Q., 2009a. Emergy-based energy and material metabolism of the Yellow River basin. Commun. Nonlinear Sci. Numer. Simul. 14, 923–934.

Chen, B., Chen, S.Q., 2013a. Life cycle assessment of coupling household biogas production to agricultural industry: a case study of biogas-linked persimmon cultivation and processing system. Energy Policy 62, 707–716.

Chen, B., Chen, Z.M., Zhou, Y., Zhou, J.B., Chen, G.Q., 2009a. Emergy as embodied energy based assessment for local sustainability of a constructed wetland in Beijing. Commun. Nonlinear Sci. Numer. Simul. 14, 622–635.

Chen, G.Q., Chen, B., 2007b. Resource analysis of the Chinese society 1980–2002 based on exergy—Part 1: Fossil fuels and energy minerals. Energy Policy 35, 2038–2050.

Chen, G.Q., Chen, B., 2009b. Extended-exergy analysis of the Chinese society. Energy 34, 1127–1144.

Chen, G.Q., Chen, H., Chen, Z.M., Zhang, B., Shao, L., Guo, S., Zhou, S.Y., Jiang, M.M., 2011a. Low-carbon building assessment and multi-scale input–output analysis. Commun. Nonlinear Sci. Numer. Simul. 16, 583–595.

Chen, G.Q., Chen, Z.M., 2010. Carbon emissions and resources use by Chinese economy 2007: a 135-sector inventory and input-output embodiment. Commun. Nonlinear Sci. Numer. Simul. 15, 3647–3732.

Chen, G.Q., Chen, Z.M., 2011a. Greenhouse gas emissions and natural resources use by the world economy: ecological input-output modeling. Ecol. Modell. 222, 2362–2376.

Chen, G.Q., Guo, S., Shao, L., Li, J.S., Chen, Z.M., 2013. Three-scale input-output modeling for urban economy: carbon emission by Beijing 2007. Commun. Nonlinear Sci. Numer. Simul. 18, 2493–2506.

Chen, G.Q., Jiang, M.M., Chen, B., Yang, Z.F., Lin, C., 2006. Emergy analysis of Chinese agriculture. Agric. Ecosyst. Environ. 115, 161–173.

Chen, G.Q., Jiang, M.M., Yang, Z.F., Chen, B., Ji, X., Zhou, J.B., 2009b. Exergetic assessment for ecological economic system: Chinese agriculture. Ecol. Modell. 220, 397–410.

Chen, G.Q., Shao, L., Chen, Z.M., Li, Z., Zhang, B., Chen, H., Wu, Z., 2011b. Low-carbon assessment for ecological wastewater treatment by a constructed wetland in Beijing. Ecol. Eng. 37, 622–628.

Chen, G.Q., Wu, Z., Zeng, L., 2012a. Environmental dispersion in a two-layer wetland: analytical solution by method of concentration moments. Int. J. Eng. Sci. 51, 272–291.

Chen, G.Q., Yang, Q., Zhao, Y.H., 2011c. Renewability of wind power in China: a case study of nonrenewable energy cost and greenhouse gas emission by a plant in Guangxi. Renewable Sustainable Energy Rev. 15, 2322–2329.

Chen, G.Q., Yang, Q., Zhao, Y.H., Wang, Z.F., 2011d. Nonrenewable energy cost and greenhouse gas emissions of a 1.5 MW solar power tower plant in China. Renewable Sustainable Energy Rev. 15, 1961–1967.

Chen, H., Chen, G.Q., Ji, X., 2010. Cosmic emergy based ecological systems modelling. Commun. Nonlinear Sci. Numer. Simul. 15, 2672–2700.

Chen, S.Q., Chen, B., 2012. Sustainability and future alternatives of biogas-linked agrosystem (BLAS) in China: an emergy synthesis. Renewable Sustainable Energy Rev. 16, 3948–3959.

Chen, S.Q., Chen, B., 2013b. Net energy production and emissions mitigation of domestic wastewater treatment system: A comparison of different biogas–sludge use alternatives. Bioresour. Technol. 144, 296–303.

Chen, S.Q., Chen, B., 2014. Energy efficiency and sustainability of complex biogas systems: a 3-level emergetic evaluation. Appl. Energy 115, 151–163.

Chen, S.Q., Chen, B., Song, D., 2012b. Life-cycle energy production and emissions mitigation by comprehensive biogas–digestate utilization. Bioresour. Technol. 114, 357–364.

Chen, Z.M., Chen, G.Q., 2011b. An overview of energy consumption of the globalized world economy. Energy Policy 39, 5920–5928.

Ciotola, R.J., Lansing, S., Martin, J.F., 2011. Emergy analysis of biogas production and electricity generation from small-scale agricultural digesters. Ecol. Eng. 37, 1681–1691.

Han, M.Y., Chen, G.Q., Shao, L., Li, J.S., Alsaedi, A., Ahmad, B., Guo, S., Jiang, M.M., Ji, X., 2013. Embodied energy consumption of building construction engineering: case study in E-town, Beijing. Energy Build. 64, 62–72.

Higgins, J.B., 2003. Emergy analysis of the Oak Openings region. Ecol. Eng. 21, 75–109.

IEA, 2011. World Energy Outlook 2011. IEA, Available online at: ⟨www.iea.org/Textbase/about/copyright.asp⟩.

Jiang, M.M., Chen, B., Zhou, J.B., Tao, F.R., Li, Z., Yang, Z.F., Chen, G.Q., 2007. Emergy account for biomass resource exploitation by agriculture in China. Energy Policy 35, 4704–4719.

Jiang, M.M., Zhou, J.B., Chen, B., Chen, G.Q., 2008. Emergy-based ecological account for the Chinese economy in 2004. Commun. Nonlinear Sci. Numer. Simul. 13, 2337–2356.

Jingzhou, 2002. Jingzhou Yearbook. Publishing House of Local Records (in Chinese).

Lei, K., Wang, Z., Ton, S., 2008. Holistic emergy analysis of Macao. Ecol. Eng. 32, 30–43.

Li, J.S., Chen, G.Q., 2013. Energy and greenhouse gas emissions review for Macao. Renewable Sustainable Energy Rev. 22, 23–32.

Li, J.S., Chen, G.Q., Lai, T.M., Ahmad, B., Chen, Z.M., Shao, L., Ji, X., 2013. Embodied greenhouse gas emission by Macao. Energy Policy 59, 819–833.

Li, J.S., Chen, G.Q., Wu, X.F., Hayat, T., Alsaedi, A., Ahmad, B., 2014. Embodied energy assessment for Macao's external trade. Renewable Sustainable Energy Rev. 34, 642–653.

Li, J.S., Duan, N., Guo, S., Shao, L., Lin, C., Wang, J.H., Hou, J., Hou, Y., Meng, J., Han, M.Y., 2012. Renewable resource for agricultural ecosystem in China: ecological benefit for biogas by-product for planting. Ecol. Inf. 12, 101–110.

Lin, C., Wei, X.M., Jiang, W.T., 2008. Emergy analysis of biogas project ecological model. In: Proceedings of International Seminar on Rural Biomass Energy & ASEAN Plus Three Forum on Biomass Energy, pp. 240–246.

Liu, Q.M., Feng, L.Y., 2013. Discussion on evaluation of rural biogas service system in China. China Biogas 31, 5–9 (in Chinese).

Meng, J., Chen, G.Q., Shao, L., Li, J.S., Tang, H.S., Hayat, T., Alsaedi, A., Alsaadi, F., 2014. Virtual water accounting for building: case study for E-town, Beijing. J. Cleaner Prod. 68, 7–15.

NDRC (National Development and Reform Commission), 2007. Medium and Long-Term Development Plan for Renewable Energy. NDRC (National Development and Reform Commission) (in Chinese).

Odum, H.T., 1983. Systems Ecology. Wiley, New York, NY.

Odum, H.T., 1988. Self-organization, transformity, and information. Science 242, 1132–1139.

Odum, H.T., 1994. Ecological and General Systems: An Introduction to Systems Ecology. University Press of Colorado, Boulder, Colo.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons, New York. NY.

Odum, H.T., Brown, M.T., Brandt-Williams, S., 2000. Handbook of Emergy Evaluation. Folio #1: Introduction and Global Budget. Center for Environmental Policy, University of Florida, Gainesville, FL.

Odum, H.T., Odum, E.P., 2000. The energetic basis for valuation of ecosystem services. Ecosystems 3, 21–23.

Olugasa, T.T., Odesola, I.F., Oyewola, M.O., 2014. Energy production from biogas: a conceptual review for use in Nigeria. Renewable Sustainable Energy Rev. 32, 770–776.

Poeschl, M., Ward, S., Owende, P., 2012. Environmental impacts of biogas deployment—Part I: Life cycle inventory for evaluation of production process emissions to air. J. Cleaner Prod. 24, 168–183.

Rehl, T., Lansche, J., Müller, J., 2012. Life cycle assessment of energy generation from biogas—attributional vs. consequential approach. Renewable Sustainable Energy Rev. 16, 3766–3775.

REN21, 2013. Renewables 2013 Global Status Report. REN21.

Ruan, W.Q., Yu, D., Zhou, H., Sun, Z.H., 2006. Development of biogas technology treating small town wastes. China Biogas 24, 28–31 (in Chinese).

Sciubba, E., Ulgiati, S., 2005. Emergy and exergy analyses: complementary methods or irreducible ideological options? Energy 30, 1953–1988.

Shao, L., Chen, G.Q., 2013. Water footprint assessment for wastewater treatment: method, indicator, and application. Environ. Sci. Technol. 47, 7787–7794.

Shao, L., Wu, Z., Chen, G.Q., 2013. Exergy based ecological footprint accounting for China. Ecol. Modell. 252, 83–96.

Song, Z.L., Zhang, C., Yang, G.H., Feng, Y.Z., Ren, G.X., Han, X.H., 2014. Comparison of biogas development from households and medium and large-scale biogas plants in rural China. Renewable Sustainable Energy Rev. 33, 204–213.

Ulgiati, S., Ascione, M., Zucaro, A., Campanella, L., 2011. Emergy-based complexity measures in natural and social systems. Ecol. Indic. 11, 1185–1190.

Ulgiati, S., Brown, M.T., Bastianoni, S., Marchettini, N., 1995. Emergy-based indices and ratios to evaluate the sustainable use of resources. Ecol. Eng. 5, 519–531.

Wang, X.L., Chen, Y.Q., Sui, P., Gao, W.S., Qin, F., Wu, X., Xiong, J., 2014. Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: an emergy evaluation based on LCA. J. Cleaner Prod. 65, 234–245.

Wei, X.M., Chen, B., Qu, Y.H., Lin, C., Chen, G.Q., 2009. Emergy analysis for 'Four in One' peach production system in Beijing. Commun. Nonlinear Sci. Numer. Simul. 14, 946–958.

Wu, X.H., Wu, F.Q., Tong, X.G., Jiang, B., 2013. Emergy-based sustainability assessment of an integrated production system of cattle, biogas, and greenhouse vegetables: insight into the comprehensive utilization of wastes on a large-scale farm in Northwest China. Ecol. Eng. 61 (Part A), 335–344.

Wu, Z., Zeng, L., Chen, G.Q., Li, Z., Shao, L., Wang, P., Jiang, Z., 2012. Environmental dispersion in a tidal flow through a depth-dominated wetland. Commun. Nonlinear Sci. Numer. Simul. 17, 5007–5025.

Xydis, G., Nanaki, E., Koroneos, C., 2013. Exergy analysis of biogas production from a municipal solid waste landfill. Sustainable Energy Technol. Assess. 4, 20–28.

Yang, J., Chen, B., 2014a. Emergy analysis of a biogas-linked agricultural system in rural China—a case study in Gongcheng Yao Autonomous County. Appl. Energy 118, 173–182.
Yang, J., Chen, B., 2014b. Extended exergy-based sustainability accounting of a household biogas project in rural China. Energy Policy 68, 264–272.
Yang, Q., Chen, B., Ji, X., He, Y.F., Chen, G.Q., 2009. Exergetic evaluation of corn-ethanol production in China. Commun. Nonlinear Sci. Numer. Simul. 14, 2450–2461.
Yang, Q., Chen, G.Q., 2012. Nonrenewable energy cost of corn-ethanol in China. Energy Policy 41, 340–347.
Yang, Q., Chen, G.Q., 2013. Greenhouse gas emissions of corn–ethanol production in China. Ecol. Modell. 252, 176–184.
Yang, Q., Chen, G.Q., Liao, S., Zhao, Y.H., Peng, H.W., Chen, H.P., 2013. Environmental sustainability of wind power: an emergy analysis of a Chinese wind farm. Renewable Sustainable Energy Rev. 25, 229–239.
Yang, Q., Wu, X.F., Yang, H.P., Zhang, S.H., Chen, H.P., 2012. Nonrenewable energy cost and greenhouse gas emissions of a pig-biogas-fish system in China. Sci. World J. 2012, 862021.
Yang, Z.F., Jiang, M.M., Chen, B., Zhou, J.B., Chen, G.Q., Li, S.C., 2010. Solar emergy evaluation for Chinese economy. Energy Policy 38, 875–886.
Yuan, X.H., Ji, X., Chen, H., Chen, B., Chen, G.Q., 2008. Urban dynamics and multiple-objective programming: a case study of Beijing. Commun. Nonlinear Sci. Numer. Simul. 13, 1998–2017.
Zhang, L.X., Pang, M.Y., Wang, C.B., 2014. Emergy analysis of a small hydropower plant in southwestern China. Ecol. Indic. 38, 81–88.
Zhang, L.X., Wang, C.B., Song, B., 2013. Carbon emission reduction potential of a typical household biogas system in rural China. J. Cleaner Prod. 47, 415–421.
Zhang, M.M., Wang, Z.F., Xu, C., Jiang, H., 2012. Embodied energy and emergy analyses of a concentrating solar power (CSP) system. Energy Policy 42, 232–238.
Zhou, J.B., 2008. Embodied ecological elements accounting of national economy. In: Ph.D. Thesis. Peking University, Beijing (in Chinese).
Zhou, J.B., Jiang, M.M., Chen, B., Chen, G.Q., 2009. Emergy evaluations for constructed wetland and conventional wastewater treatments. Commun. Nonlinear Sci. Numer. Simul. 14, 1781–1789.
Zhou, S.Y., Zhang, B., Cai, Z.F., 2010. Emergy analysis of a farm biogas project in China: a biophysical perspective of agricultural ecological engineering. Commun. Nonlinear Sci. Numer. Simul. 15, 1408–1418.